Can Gamma Ray Bursts Produce the Observed Cosmic Rays Above 10^{20} eV?

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Abstract

It has been suggested that cosmological γ-ray bursts (GRBs) can produce the observed flux and spectrum of cosmic rays at the highest energies. However, recent observations indicate that the redshift distribution of GRBs most likely follows that of the star formation rate in the universe, a rate which was much higher at redshifts 1.5-2 than it is today. Thus, most GRBs are at high redshifts. As a consequence, any cosmic rays emitted by these GRBs at energies above $\sim 2 - 3 \times 10^{19}$ eV would be strongly attenuated by interactions with the 3 K background radiation. If one assumes rough equality between the energy released by GRBs in $\sim 10^{-2}$ to ~ 1 MeV photons and that released in 10^{20} eV cosmic rays, then less than 10% of the cosmic rays observed above 10^{20} eV can be accounted for by GRBs.

Key words: gamma-ray bursts; cosmic rays; theory

1 Introduction

It has been suggested that cosmological γ-ray bursts can produce the observed flux of cosmic rays at the highest energies [1], [2]. The arguments as stated in Ref. [1] rest on four assumptions: (A) the highest energy cosmic rays are extragalactic, (B) cosmic rays can be accelerated to these energies in γ-ray burst fireballs, (C) the energy emitted by the bursts in ultrahigh energy cosmic rays is roughly equal to the electromagnetic energy emitted by the bursts (primarily in hard X-rays and soft γ-rays), and (D) the bursts have comoving density distribution which is independent of redshift, *i.e.* there is no cosmological evolution.

While neither accepting or addressing assumptions (B) and (C), in this paper, I will argue that assumption (D) has become implausible when one considers the recent redshift information obtained by locating the afterglow radiation from the bursts in host galaxies with measured redshifts. These studies place almost all γ-ray bursts (GRBs) with redshift assignments at moderate or high redshifts. Host galaxy studies imply that the GRB redshift distribution should follow the strong redshift dependence of the star formation rate in galaxies (see section 3 below). A further implication is that the spatial density of γ-ray bursts at low redshifts would be too low to produce the observed flux of cosmic rays above 10^{20} eV, since those cosmic rays can only reach us unattenuated in energy from distances of ~ 100 Mpc or less [3], [4], corresponding to redshifts $z \lesssim\sim 10^{-2}$.

2   The Energetics Argument for Non-evolving GRBs

If one assumes that GRBs have a redshift independent co-moving distribution, the energetics argument [1],[5] can be summarized quite succinctly. If one takes the observed rate of GRBs and averages it out over the volume of the observable universe, one finds an average rate per unit volume of $r_{GRB} \simeq 1.5 \times 10^{-8}$ Mpc^{-3}yr^{-1} (taking the Hubble constant in units of 100 km s^{-1}Mpc^{-1}, $h_0 = 0.7$. If one then takes an average total energy release per burst of $\sim 4\times10^{52}$ erg in γ-rays (from the no evolution model of Schmidt [6]) and equates this to the energy released in ultrahigh energy cosmic rays, one finds a cosmic-ray energy input rate into intergalactic space of $\sim 6 \times 10^{44}$ erg Mpc^{-3}yr^{-1}.

Taking the differential cosmic ray spectrum given by Takeda, *et al.* [7], which fits a $E^{-2.78}$ power law for energies above 10^{19} eV, one finds a cosmic ray energy flux between 10^{20} eV and 3×10^{20}eV of $\Phi_{20} = 1.7$ erg m^{-2}sr^{-1}yr^{-1}. Using the similar power-law spectrum given by Bird *et al.* [8], one finds an identical result. Taking a mean propagation distance of $L \leq 100$ Mpc for cosmic rays with energies above 10^{20} eV [3], one then finds that the required cosmic ray energy generation rate per unit volume required to explain the flux of cosmic rays in the 1-3 $\times10^{20}$ eV energy range is $(4\pi\Phi_{20})/L \geq 2.1 \times 10^{44}$ erg Mpc^{-3}yr^{-1}.

The numbers given at the ends of the last two paragraphs are interestingly similar. Thus, if as previously postulated, *e.g.*, [1],[5], a substantial fraction of the total GRB energy is released in ultrahigh energy cosmic rays as in γ-rays, GRBs can account for the observed particles above 10^{20} eV. As we will see, however, this argument is invalidated if one takes account of the redshift distribution of GRBs.

3 The Redshift Distribution of GRBs and its Implications

The advent of the *BeppoSAX* X-ray telescope and the discovery of GRB X-ray [9], optical [10], and radio [11] afterglows and the subsequent identification of host galaxies has led to the determination of the redshifts of some 11 GRBs from 1997 to date. Of these, 10 are at moderate to high redshifts and the remaining one, GRB980425, has been identified with a nearby unusual Type Ic supernova, SN 1998bw [12] with an energy release ($\sim 5 \times 10^{47}$ erg) which is orders of magnitude smaller than the typical cosmological GRB. (In fact, it is not completely established whether the supernova was indeed the source of the GRB, as another fading X-ray source was a possible contender [13]). The GRB with the highest identified redshift to date, GRB971214, lies at a redshift of 3.42 [14].

The positions of the bursts within the host galaxies and their apparent association with significant column densities of hydrogen and evidence of associated dust extinction [14], [15] has led to their association with regions of active star formation. Analyses of the colors of various host galaxies of GRBs has indicated that these galaxies are sites of active star formation [14], [16], [17] and this conclusion is strengthened by morphology studies and the detection of [OII] and Lyα emission lines in several host galaxies [14], [18], [19].

The association of GRBs with active star formation, together with the known strong redshift evolution of the star formation rate (*e.g.*, [20]) has led to theoretical examinations testing whether a uniform comoving density redshift distribution or one which follows the star formation rate fits the GRB data best [21]- [25]. Mao & Mo [25] give a discussion of the nature of the host galaxies of GRBs and argue for strong redshift evolution of GRBs. The general conclusions of Mao & Mo [25] regarding the redshift distribution of GRBs are further supported in the most recent work [6], [26],[27].

4 GRB Redshift Evolution Leads to a Strong Energetics Problem

Mao & Mo [25] find that their best fit model corresponds to a GRB redshift distribution following the star formation rate which would have a *present rate* ($z \simeq 0$) of $\simeq 1.7 \times 10^{-10} h_0^3$ Mpc^{-3}yr^{-1} and a mean energy release of $\sim 10^{52} h_0^{-2}$ erg per burst in the 50 to 300 keV band. Using more recent data, Schmidt [6] has given an analysis of the luminosities and space densities of GRBs. His analysis also points to a strong evolution in redshift, similar to that of the star formation rate. He finds a present local GRB rate per unit volume of $\simeq 1.8 \times 10^{-10}$ Mpc^{-3}yr^{-1} with h_0 taken to be 0.7. Schmidt also finds a characteristic total energy release per burst of 1.2×10^{53} erg over the energy

range from 10 to 1000 keV. I will adopt Schmidt's more recent results [6] for my discussion in this paper. The corresponding energy release rate per unit volume would then be $\sim 2 \times 10^{43}$erg Mpc^{-3}yr^{-1}. *This is an order of magnitude below the rate needed to explain the ultrahigh energy cosmic rays, as indicated in Section 2 above.* Therefore, even if we make the assumption of a rough equality between the typical energy released by a GRB in γ-rays and that released in ultrahigh energy cosmic-rays [1],[5], we still fall significantly short of the energy input rate needed to explain the cosmic ray observations.

Another way of stating this result is that for GRBs to be the source of the observed cosmic rays above 10^{20} eV, they would have to put at least an order of magnitude more energy into $\sim 10^{14}$ MeV protons than into $\sim$ MeV photons. This would increase the required *total* GRB energy to $\geq 10^{54}$ erg and require GRBs to release at least 90% of their energy in the form of ultrahigh energy protons.

5   Other Considerations

There are other considerations which support the thesis presented here that the GRBs are unlikely to produce the observed ultrahigh energy cosmic rays. Beaming is not a way out. While it is true that if GRBs are beamed into a solid angle Ω, we only see $(\Omega/4\pi)$ of them, the energy release per burst would also be lower by the same factor of $\Omega/4\pi$ and the total energy release rate per unit volume is unchanged. Also, if the evolving redshift distribution scenario for GRBs is correct, there will not be large numbers of faint GRBs nearby; the faintest GRBs seen will corrrespond to GRBs which are at the highest redshifts. (Even if the redshift distribution of bursts were more uniform than the star formation rate assumed here, this would imply that the average energy release per burst would be lower in order to fit the observed flux distribution, since there would be more nearby sources.)

Could Type I supernovae produce the observed ultrahigh energy cosmic rays? Let us assume that SN 1998bw is the source of GRB980425 and that some fraction of Type I SN are γ-ray bursters with a typical energy of $\sim 5 \times 10^{47}$ erg and a peak flux of $\sim 3 \times 10^{-7}$ erg cm^{-2}s^{-1} in the *BATSE* range (as per GRB980425). Given its threshold flux, *BATSE* would be able to detect such sources distributed uniformly at a maximum rate of ~ 60 yr^{-1} (taking the upper limit of 6% of the total burst rate given in Ref. [28]) out to a distance of ~ 53 Mpc. The corresponding energy release rate would then be $\sim 3 \times 10^{49}$ erg in a volume of $(4\pi)/3 \times (53)^3$ Mpc^3 or $\sim 5 \times 10^{43}$ erg Mpc^{-3}yr^{-1}. This is only a factor of ~ 4 lower than the required rate (see section 2). However, this is an upper limit, given the statistical arguments against this hypothesis associating GRBs with Type I supernovae [28] and [29]. In addition, one may

note that while a typical GRB has a "high energy" photon spectral index of 2.1, GRB980425 had a spectral index above ~ 150 keV of ~ 4, calling into question whether such a source could produce ultrahigh energy cosmic rays.

6   The Spectrum of Ultrahigh Energy Cosmic Rays

Finally, I wish to comment on the spectrum of cosmic rays seen above 10^{20} eV. Waxman [5] has argued that the present cosmic ray data may be still statistically consistent with a uniform GRB distibution in redshift, even though no cosmological cutoff is seen corresponding to the so-called GZK effect [30], [31], [3]. The GZK effect should manifest itself in a steepening of the cosmic ray spectrum above an energy of $\sim 7 \times 10^{19}$ eV (*e.g.*, [32]). If, as argued here however, the GRBs are cosmic-ray sources overwhelmingly at moderate to high redshifts, the GZK effect comes in at lower energies (by a factor of $(1+z)^2$) and the attenuation will be much more severe since the GZK process involves cosmic ray energy loss from photopion production off the 3K cosmic background radiation (which would actually have a temperature of $3[1+z]$K) and the photon (target) density of this background would be higher by a factor of $(1+z)^3$). One thus expects to see a dramatic reduction in the observed flux above $\sim 10^{19}$eV and *no* observable 10^{20} eV cosmic rays except those coming from redshifts, $z \ll 1$ (see, *e.g.*, [33],[34]). This is in strong contradiction to the observations ([35],[36],[7]. This drastic conflict between the observed spectrum and that predicted for the redshift distribution of GRBs will be presented in detail in a subsequent paper [37].

7   Conclusion

Given all of the above considerations, it would appear that there is no compelling reason to believe that GRBs can produce the observed flux of ultrahigh energy cosmic rays. Indeed, given the knowledge obtained from recent observations of GRBs, there appear to be many problems with this hypothesis, making it highly questionable.

8   Acknowledgments

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